

Determination of absolute neutrino masses from Z-bursts

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Ultrahigh energy neutrinos (UHE ν) scatter on cosmological relic neutrinos (R ν) producing Z bosons, which can decay hadronically producing protons (Z-burst). We compare the predicted proton spectrum with the observed ultrahigh energy cosmic ray (UHECR) spectrum and determine the mass of the heaviest R ν via a maximum likelihood analysis. Our mass prediction depends on the origin of the power-like part of the UHECR spectrum: $m_\nu = 2.34^{+1.29}_{-0.84}$ eV for Galactic halo and $0.26^{+0.20}_{-0.14}$ eV for extragalactic (EG) origin. The second mass, with a lower bound of 0.06 eV on the 95% confidence level (CL), is compatible with a hierarchical ν mass scenario with the largest mass suggested by the atmospheric ν oscillation. The necessary UHE ν flux is compatible with present upper limits and should be detected in the near future.

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I. Introduction. — The interaction of protons (p) with photons of the cosmic microwave background radiation (CMBR) predicts a sharp drop in the cosmic ray flux above the Greisen-Zatsepin-Kuzmin (GZK) cutoff around $4 \cdot 10^{19}$ eV [1]. The available data show no such drop. About 20 events above 10^{20} eV were observed by experiments such as AGASA [2], Fly's Eye [3], Haverah Park [4], Yakutsk [5], and HiRes [6]. The attenuation length of protons above the GZK cutoff is ≈ 50 Mpc; but no obvious astrophysical source candidate is known within this distance. No conventional explanation for the observed UHECR spectrum is known [7].

Already in the early 80's there were discussions that the UHE ν spectrum could have absorption dips at energies around $E_{\nu_i}^{\text{res}} = M_Z^2/(2m_{\nu_i}) = 4.2 \cdot 10^{21}$ (1 eV/ m_{ν_i}) eV due to resonant annihilation with the R ν s, predicted by the hot Big Bang cosmology, into Z bosons of mass M_Z [8,9]. Recently it was realized that the same annihilation mechanism gives a possible solution to the GZK problem [10]. It was argued that the UHECRs above the GZK cutoff are mainly from Z-bursts taking place within the GZK zone of ≈ 50 Mpc.

This hypothesis was discussed in several papers. In Ref. [11], particle spectra were determined numerically for case studies which supported the Z-burst scenario. The required UHE ν fluxes for different spectral indices were calculated in Ref. [12], too. The effect of possible lepton asymmetries was studied in Ref. [13]. In Ref. [14], the analysis of the Z-burst mechanism was advocated as one of the few possibilities for an absolute ν mass determination and its potential compared to others like e.g. the β decay endpoint spectrum and the ν -less $\beta\beta$ decay.

There is now rather convincing evidence that ν s have nonzero masses (cf. [15]). This evidence comes from ν oscillation measurements with typical mass splittings $\sqrt{\delta m^2} \sim 10^{-5} \div 0.4$ eV. Neutrinos in this mass range are important cosmologically since they represent a non-negligible contribution to dark matter (DM) which im-

poses upper limits on ν masses [16]. Hydrodynamic simulations with massive ν s and including recent observational measurements and cosmological constraints give [17] $\sum_i m_{\nu_i} \lesssim 2.4 \cdot (\Omega_M/0.17 - 1)$ eV, if the matter content of the universe Ω_M is assumed to be between 0.2 and 0.5, as favoured by recent measurements (cf. [15]).

In Section II we derive the observable proton spectrum from Z-bursts. This prediction is compared with the observed UHECR spectrum, from which we determine the R ν mass. Section III discusses the necessary UHE ν flux and its present and future observational possibilities.

II. Z-burst spectrum and UHECR data. — Our comparison of the Z-burst scenario with the observed UHECR spectrum is done in four steps. First we determine the probability of Z production as a function of the distance from earth. In the second step we exploit collider experiments to derive the energy distribution of the produced protons in the lab system. The third ingredient is the propagation of the protons, i.e. the determination of their energy loss due to pion and e^+e^- production through scattering on the CMBR and due to their redshift. The last step is the comparison of the predicted and observed spectrum and the extraction of the mass of the R ν and the necessary UHE ν flux.

For a given neutrino type i the probability of Z-bursts at some distance r is proportional to the number density $n_{\nu_i}(r)$ of the R ν s and to the flux $F_{\nu_i}(E_{\nu_i}, r)$ of the UHE ν s at energy $E_{\nu_i} \approx E_{\nu_i}^{\text{res}}$. The density distribution of R ν s as hot DM follows the total mass distribution; however, it is expected to be less clustered. This is the reason why we, as opposed to practically all previous authors [10–12], do not follow the unnatural assumption of having a relative overdensity of $10^2 \div 10^4$ in our neighbourhood. For distances below 100 Mpc we varied the shape of the $n_{\nu_i}(r)$ distribution between the homogeneous case and that of $m_{\text{tot}}(r)$, the total mass distribution obtained from peculiar velocity measurements [18]. Our results are rather insensitive to these variations. Their effect is

included in our error bars. For scales larger than 100 Mpc the $R\nu$ density is given by the Big Bang cosmology, $n_{\nu_i} = 56 \cdot (1+z)^3 \text{ cm}^{-3}$. In our analysis we go up to distances of redshift $z = 2$ (cf. [19]). We include uncertainties of the expansion rate (see e.g. Sect. 2 of [15]). The UHE ν flux is assumed to have the form $F_{\nu_i}(E_{\nu_i}, r) = F_{\nu_i}(E_{\nu_i}, 0) (1+z)^\alpha$, where α characterizes the source evolution (see also [9,11]). Note, that, independently of the production mechanism, ν oscillations result in a uniform F_{ν_i} mixture for the different types i .

The Z-burst scenario is based on Z decays. At LEP and SLC millions of Z bosons were produced and their decay analyzed with extreme high accuracy. 69.89% of the Z decays are hadronic and the $p + \bar{p}$ multiplicity is $\langle N_p \rangle = 1.04 \pm 0.04$ in the hadronic channel [15]. The neutron multiplicity, which we included in our analysis, is $\approx 4\%$ smaller than the proton's [20]. We combined existing published and some improved unpublished data on the momentum distribution $\mathcal{P}(x = p_{\text{proton}}/p_{\text{beam}})$ of protons in Z decays [21]. Due to the large statistics, the uncertainties of our analysis related to Z decay are negligible.

In the CM system of the Z production the angular distribution of the hadrons is determined by the spin 1/2 of the primary quarks and thus proportional to $1 + w^2 = 1 + \cos^2 \theta$ (here θ is the angle between the incoming neutrinos and the outgoing hadrons (cf. [22])). The energy distribution $\mathcal{Q}(E_p)$ of the produced protons with energy E_p is finally obtained after a Lorentz transformation from the CM system to the lab system,

$$\mathcal{Q}(E_p) = \sum_{+, -} \frac{3}{8} \int_{-1}^1 dw (1 + w^2) \quad (1)$$

$$\frac{1}{1 - w^2} \left| \frac{\pm y - w \sqrt{y^2 - (1 - w^2)(2m_p/M_Z)^2}}{E_\nu/2 \cdot \sqrt{y^2 - (1 - w^2)(2m_p/M_Z)^2}} \right|$$

$$\mathcal{P} \left([wy \pm \sqrt{y^2 - (1 - w^2)(2m_p/M_Z)^2}] / (1 - w^2) \right),$$

where m_p is the p mass and $y = 2E_p/E_\nu$. The first line comes from the angular distribution, the second line is the Jacobian and the third one is the momentum distribution at the inverted momentum.

Particles of EG origin and energies above $\approx 4 \cdot 10^{19}$ eV lose a large fraction of their energies [1]. This can be quantitatively described by the function $P(r, E_p, E)$, the probability that a proton created at a distance r with energy E_p arrives at Earth above the threshold energy E [23]. It has been calculated for a wide range of parameters in Ref. [24]. Only UHECR photons (γ s) produced in our close vicinity can reach us. Since we go up to distances with $z = 2$, their contribution is negligible.

Our prediction of the Z-burst contribution to the UHECR spectrum, for degenerate ν masses ($m_\nu \approx m_{\nu_i}$), can thus be summarized as

$$j(E, m_\nu) = I \cdot F_Z^{-1} \cdot \int_0^\infty dE_p \int_0^{R_0} dr \int_0^\infty d\epsilon \quad (2)$$

$$\sum_i F_{\nu_i}(E_{\nu_i}, r) \sigma(\epsilon) n_{\nu_i}(r) \mathcal{Q}(E_p) (-\partial P(r, E_p, E) / \partial E),$$

where $I \approx 8 \cdot 10^{16} \text{ m}^2 \cdot \text{s} \cdot \text{sr}$ is the total time and angle integrated detector area (estimated from the highest energy events and the corresponding fluxes), R_0 is the distance at $z = 2$, and $\sigma(\epsilon)$ is the Z production cross section at CM energy $\epsilon = (2m_\nu E_{\nu_i})^{1/2}$. The normalization factor F_Z is proportional to the sum of the ν fluxes at CM energy M_Z .

We compare the spectrum (2) with the observed one and give the value of m_ν based on a maximum likelihood analysis. In the Z-burst scenario a small $R\nu$ mass needs large E_ν^{res} in order to produce a Z. Large E_ν^{res} results in a large Lorentz boost, thus large E_p . In this way the detected E determines the mass of the $R\nu$.

Our analysis includes the published and the unpublished (from the www pages of the experiments on 17/03/01) UHECR data of [2–4,6]. Due to normalization difficulties we did not use the Yakutsk [5] results.

Since the Z-burst scenario results in a quite small flux for lower energies, the “ankle” is used as a lower end for the UHECR spectrum: $\log(E_{\text{min}}/\text{eV}) = 18.5$. Our results are insensitive to the definition of the upper end (the flux is extremely small there) for which we choose $\log(E_{\text{max}}/\text{eV}) = 26$. As usual, we divided each logarithmic unit into ten bins. The integrated flux gives the total number of events in a bin. The uncertainties of the measured energies are about 30% which is one bin. Using a Monte-Carlo method we included this uncertainty in the final error estimates. For the degenerate case, the predicted number of events in a bin is given by

$$N(i) = \int_{E_i}^{E_{i+1}} dE [A \cdot E^{-\beta} + F_Z \cdot j(E, m_\nu)], \quad (3)$$

where E_i is the lower bound of the i^{th} energy bin. The first term is the usual power law behavior, which describes the data well for smaller energies [2]. For this term we will study two possibilities. In the first case we assume that the power part is produced in our galaxy. Thus no GZK effect should be included for it (“halo”). In the second – in some sense more realistic – case we assume that the protons come from uniformly distributed, EG sources and suffer from the GZK cutoff (“EG”). In this case the simple power-law-like term will be modified and falls off around $4 \cdot 10^{19}$ eV (see later Fig. 1). The second term of the flux in Eq. (3) corresponds to the spectrum of the Z-bursts, Eq. (2). A and F_Z are normalization factors.

The expectation value for the number of events in a bin is given by Eq. (3) and it is Poisson distributed. To determine the most probable value for m_ν we used the maximum likelihood method and minimized [25] the $\chi^2(\beta, A, F_Z, m_\nu)$ for Poisson distributed data [15],

$$\chi^2 = \sum_{i=18.5}^{26.0} 2 [N(i) - N_o(i) + N_o(i) \ln (N_o(i)/N(i))], \quad (4)$$

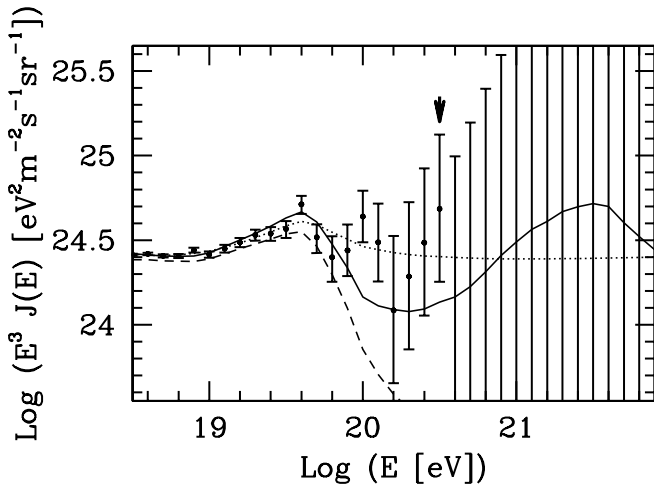


FIG. 1. The available UHECR data with their error bars and the best fits from Z-bursts. Note that there are no events above 3×10^{20} eV (shown by an arrow). Bins with no events show the 1σ upper bounds on the flux. Therefore the experimental value of the integrated flux is in the “hatched” region with 68% confidence level (“hatching” is a set of individual error bars; though most of them are too large to be depicted in full). The dotted line shows the best fit for the “halo”-case. The bump around $4 \cdot 10^{19}$ eV is due to the Z-burst protons, whereas the almost horizontal contribution is the first, power-law-like term of Eq. (3). The solid line shows the “extragalactic”-case. The first bump at $4 \cdot 10^{19}$ eV represents protons produced at high energies and accumulated just above the GZK cutoff due to their energy losses. The bump at $3 \cdot 10^{21}$ eV is a remnant of the Z-burst energy. The dashed line shows the contribution of the power-law-like spectrum with the GZK effect included. The predicted fall-off for this term around $4 \cdot 10^{19}$ eV can be observed.

where $N_o(i)$ is the total number of observed events in the i^{th} bin. In our fitting procedure we have four parameters: β , A , F_Z and m_ν . The minimum of the $\chi^2(\beta, A, F_Z, m_\nu)$ function is χ^2_{\min} at $m_{\nu \min}$ which is the most probable value for the mass, whereas $\chi^2(\beta', A', F'_Z, m_\nu) \equiv \chi^2_o(m_\nu) = \chi^2_{\min} + 1$ gives the 1σ (68%) confidence interval for m_ν . Here β' , A' , F'_Z are defined in such a way that the $\chi^2(\beta, A, F_Z, m_\nu)$ function is minimized in β , A and F_Z at fixed m_ν .

Our best fits to the observed data can be seen in Fig. 1, for evolution parameter $\alpha = 1$. The neutrino mass is $2.34^{+1.29(3.74)}_{-0.84(1.66)}$ eV for the “halo”- and $0.26^{+0.20(0.50)}_{-0.14(0.22)}$ eV for the “EG”-case, respectively. The first numbers are the 1σ , the numbers in the brackets are the 2σ errors. This gives an absolute lower bound on the mass of the heaviest ν of 0.06 eV at the 95% CL. The fits are rather good; for 21 non-vanishing bins and 4 fitted parameters they can be as low as $\chi^2 = 15.1$. We determined m_ν for a wide range of cosmological source evolution ($\alpha = 0 \div 3$) and Hubble parameter ($H_0 = 0.64 \div 0.78$ km/sec/Mpc) and observed only a moderate dependence on them. The results remain within the above error bars. For these

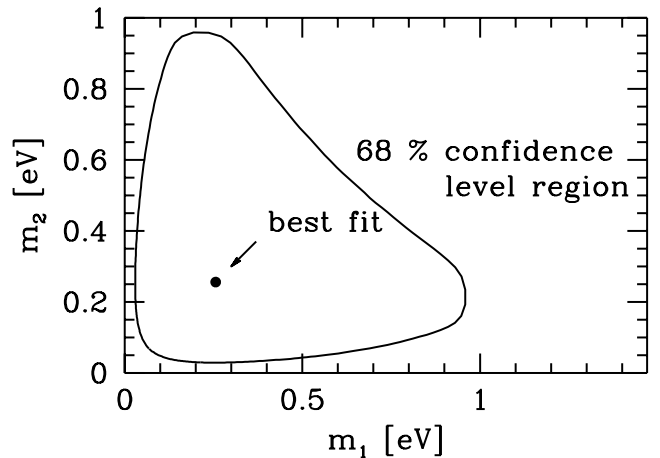


FIG. 2. The best fit and the 1σ (68% confidence level) region in a scenario with two non-degenerate ν masses.

mass scales the atmospheric or solar ν experiments suggest practically degenerate ν masses. This has no influence on our ν mass determination; however, it has to be taken into account in our flux determination.

We performed a Monte-Carlo analysis studying higher statistics. In the near future, Auger [26] will provide a ten times higher statistics, which reduces the error bars in the neutrino mass to \approx one third of their present values.

One of the most attractive patterns for ν masses is similar to the one of the charged leptons or quarks: the masses are hierarchical, thus the mass difference between the families is approximately the mass of the heavier particle. Using the mass difference of the atmospheric ν oscillation for the heaviest mass [15], one obtains values between 0.03 and 0.09 eV. It is an intriguing feature of our result that the smaller one of the predicted masses is compatible on the $\approx 1.3\sigma$ level with this scenario.

Another popular possibility is to have 4 neutrino types. Two of them – electron and sterile neutrinos – are separated by the solar ν oscillation solution, the other two – muon and tau – by the atmospheric ν oscillation solution, whereas the mass difference between the two groups is of the order of 1 eV. We studied this possibility, too. On our mass scales and resolution the electron and sterile neutrinos are practically degenerate with mass m_1 and the muon and tau neutrinos are also degenerate with mass m_2 . The best fit and the 1σ region in the $m_1 - m_2$ plane is shown in Fig. 2 for the “EG”-case. Since this two-mass scenario has much less constraints the allowed region for the masses is larger than in the one-mass scenario.

III. Necessary UHE ν flux. — The necessary UHE ν flux at E_ν^{res} can be obtained via Eqs. (2) and (3) from our fits. We have summarized them in Fig. 3, together with some existing upper limits and projected sensitivities of present, near future and future observational projects. It is apparent that the flux determination depends much more on the evolution uncertainties than the mass deter-

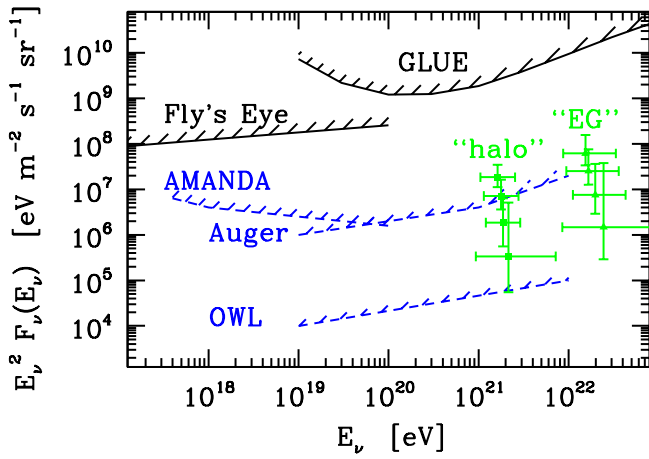


FIG. 3. Differential neutrino fluxes required by the Z-burst hypothesis for the “halo” and the “extragalactic” case. The evolution parameter α takes values 0,1,2,3 from top to bottom for both cases, respectively. The horizontal errors indicate the 1σ uncertainty of the mass determination and the vertical errors include also the uncertainty of the Hubble expansion rate. Also shown are upper limits from Fly’s Eye [27] and the Goldstone lunar ultrahigh energy neutrino experiment GLUE [28], as well as projected sensitivities of AMANDA [29], Auger [11,30] and OWL [11,31].

mination. The necessary ν flux appears to be well below present upper limits and is within the expected sensitivity of AMANDA, Auger, and OWL. As a cross check, we have calculated the total energy in γ s from Z-bursts. We assumed that all the energy ends up between 30 MeV and 100 GeV and compared it with the EGRET observations [32]. Our γ flux is smaller than that of EGRET.

IV. Conclusions. — We compared the predicted spectrum of the Z-burst hypothesis with the observed UHE-CR spectrum. We should emphasize, that, for the first time in the literature, no unnatural overdensity of $R\nu$ s was used. We determined the mass of the heaviest $R\nu$: $m_\nu = 2.34^{+1.29}_{-0.84}$ eV for halo and $0.26^{+0.20}_{-0.14}$ eV for EG scenarios. The second mass, with a lower bound of 0.06 eV on the 95% CL, is compatible with a hierarchical ν mass scenario with the largest mass suggested by the atmospheric ν oscillation. We analysed a possible two-mass scenario and gave the corresponding confidence level region. The necessary UHE ν flux is consistent with present upper limits and should be detected in the near future.

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